

Reliability of Microchannel Coolers for High Heat Flux Power Electronics Applications



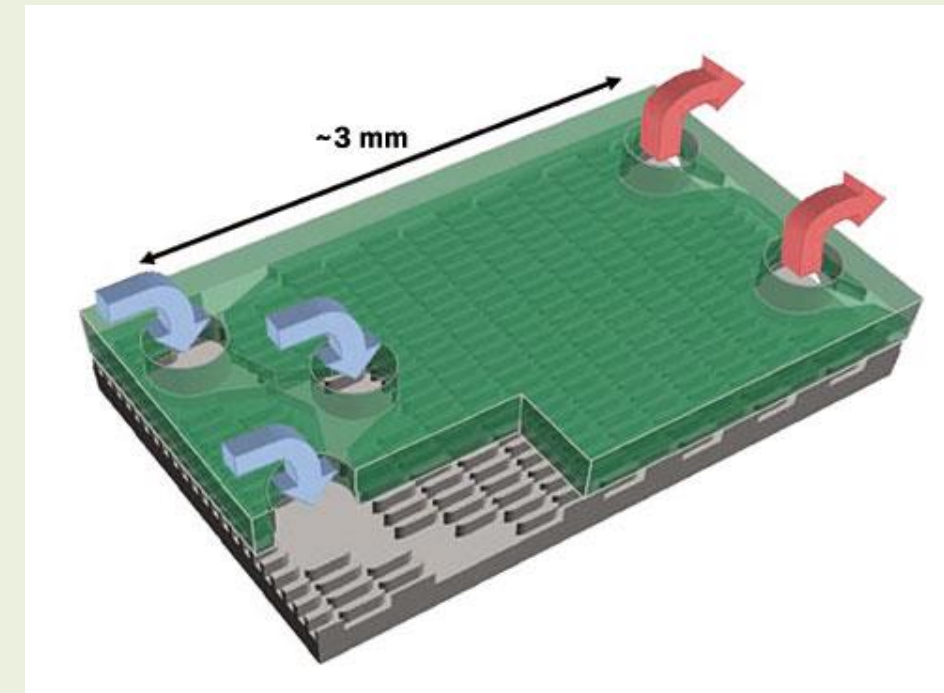
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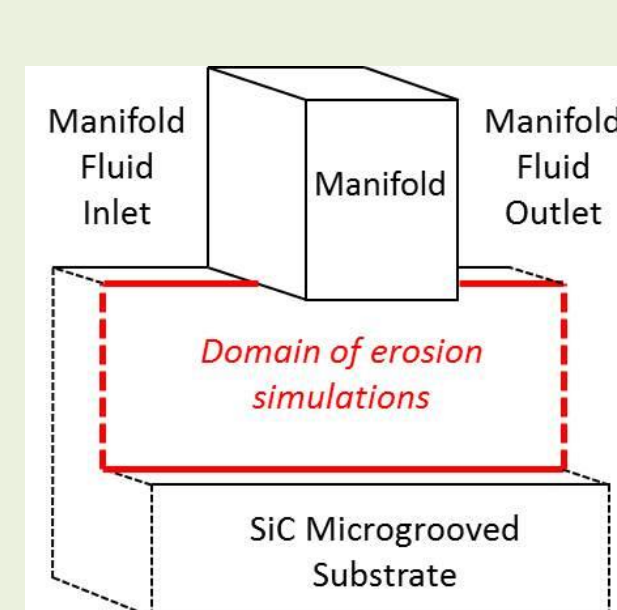
Thermal & Fluids Analysis Workshop, August 2015

Overview of Microchannel Coolers

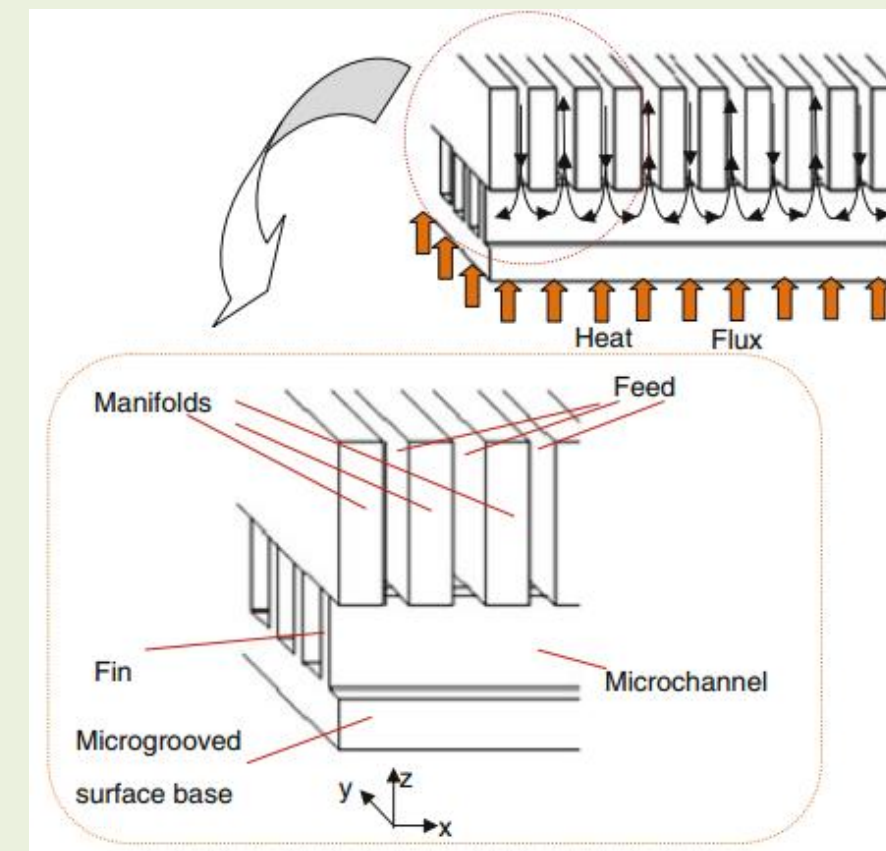
- Can be embedded directly into the substrate to provide highly localized heat removal.
- Many different forms: single vs. two phase fluid, silicon or ceramic substrate vs. alloys, working fluids, velocity, temperature, filtering, etc.
- No “one-size-fits-all” reliability solution.



3D Rendering of Si Microchannel Cooler (Colgan 2007)

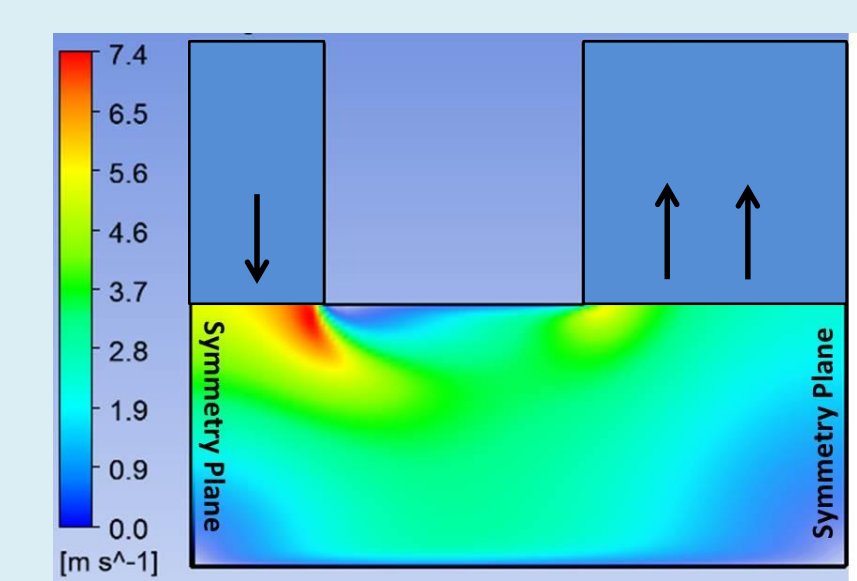


Force-Fed Microchannel Heat Exchanger (Ohadi 2013)

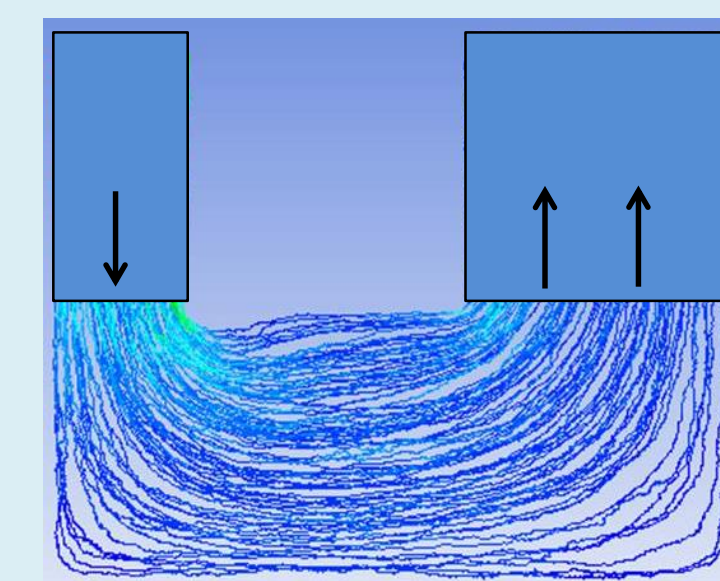


Fundamentals of CFD Erosion Modeling

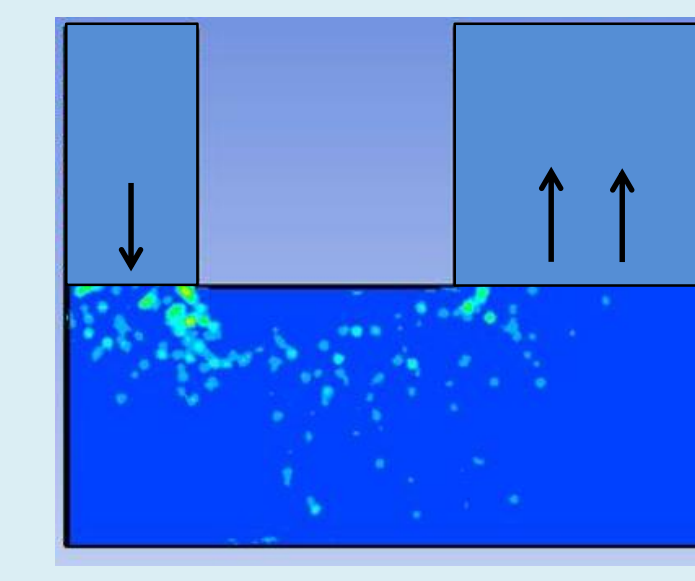
- Widely used in the Oil & Gas industry
- Conducted in three primary steps:
 - 1) Numerically compute flow field
 - 2) Calculate particle trajectories
 - 3) Model particle-wall interactions (erosion equation)



Computation of flow field using commercial CFD Code



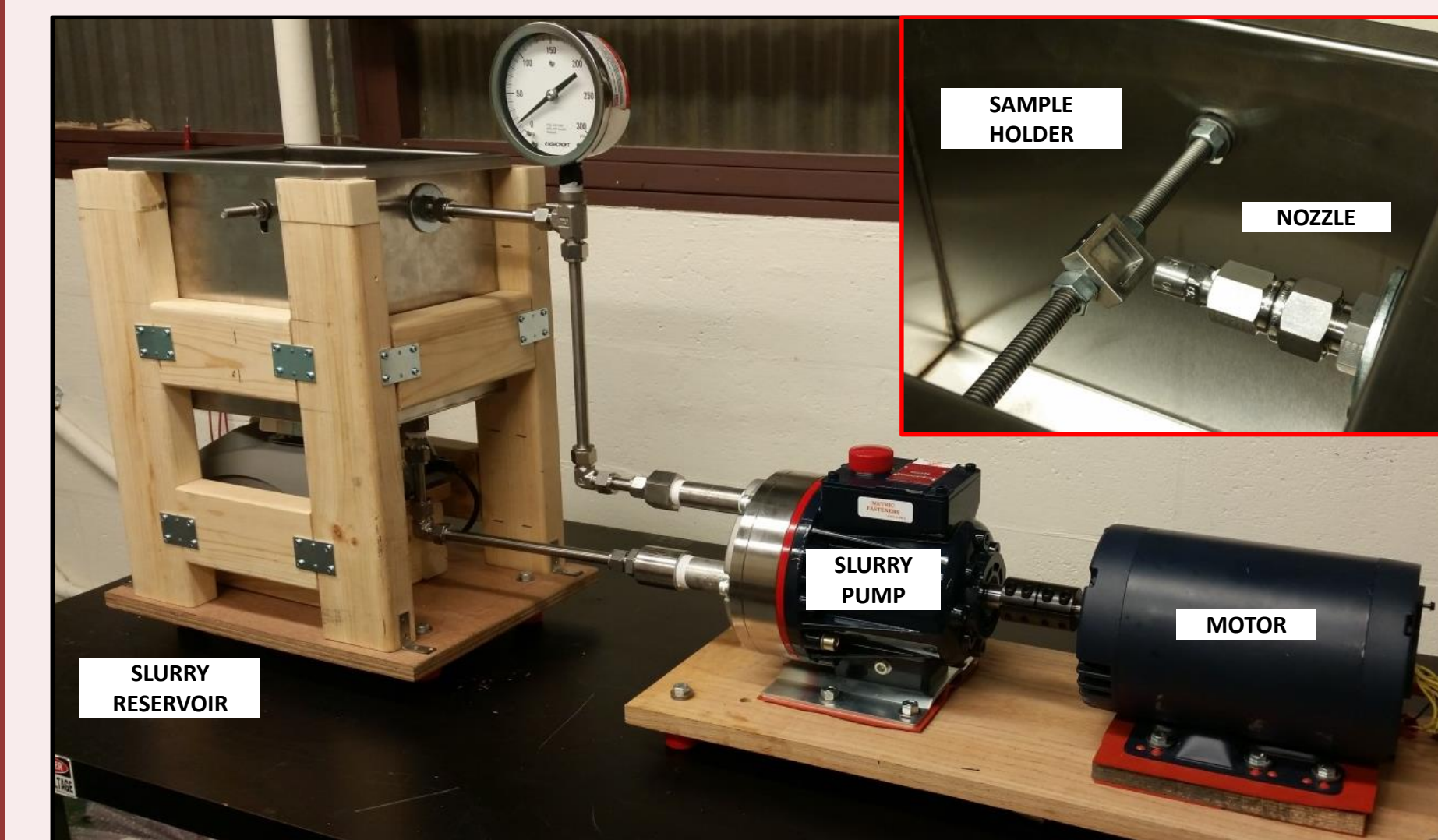
Coupling particle trajectories to flow field



Generation of erosion contours based on particle-wall interaction equation

Slurry Erosion Testing

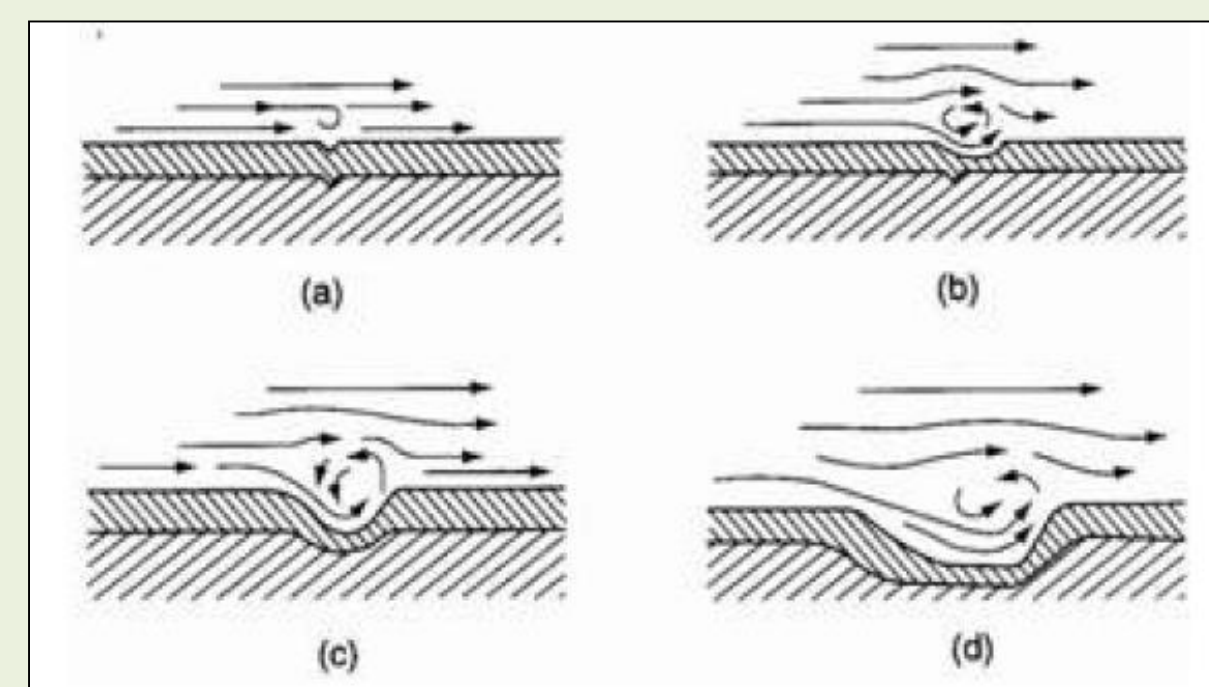
- Gain insight into the removal mechanism of the various materials involved in microchannel coolers.
- Determine and calibrate model to predict erosion in microchannel coolers. Identify threshold velocities and particle diameters.



Factor Ranges:

Velocities: 5 – 60 m/s
Particle Sizes: 0.1 – 25 μm
Particle Conc.: 0 – 1% (m/m)
Impingement Angles: 0 – 90°
Materials: SiC, Al_2O_3 , SS

Degradation Mechanisms



Erosion-Corrosion Phenomena (www.corrosionlab.com)

Erosion: Entrained particles impinge on the walls altering channel geometry and generating particulates.

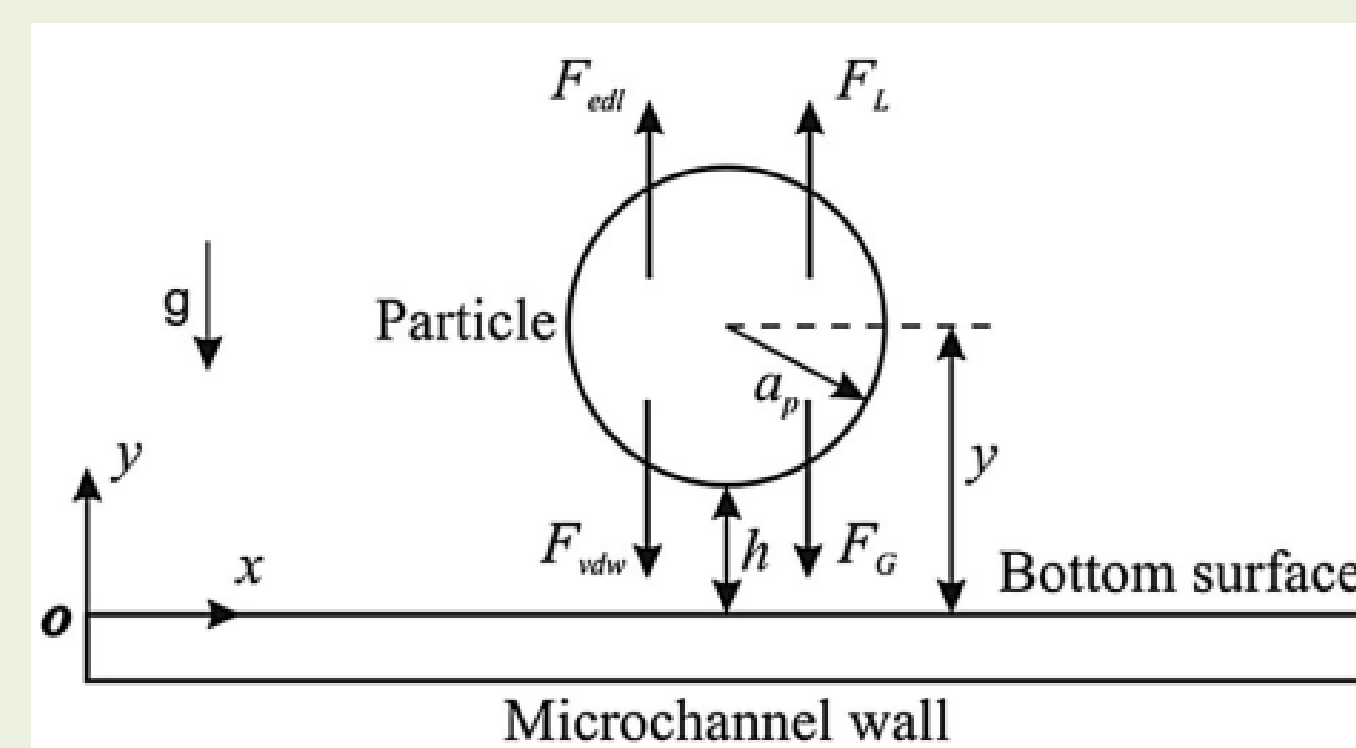
Corrosion: Relatively uniform dissolution of material into solution, and formation of brittle oxide layers.

Clogging/fouling: Entrained particles become attracted to channel surfaces. Layers of particles form eventually leading to full blockage.

Van Der Waals Force (F_{vdw}):
Attractive force between particles or particle to wall.

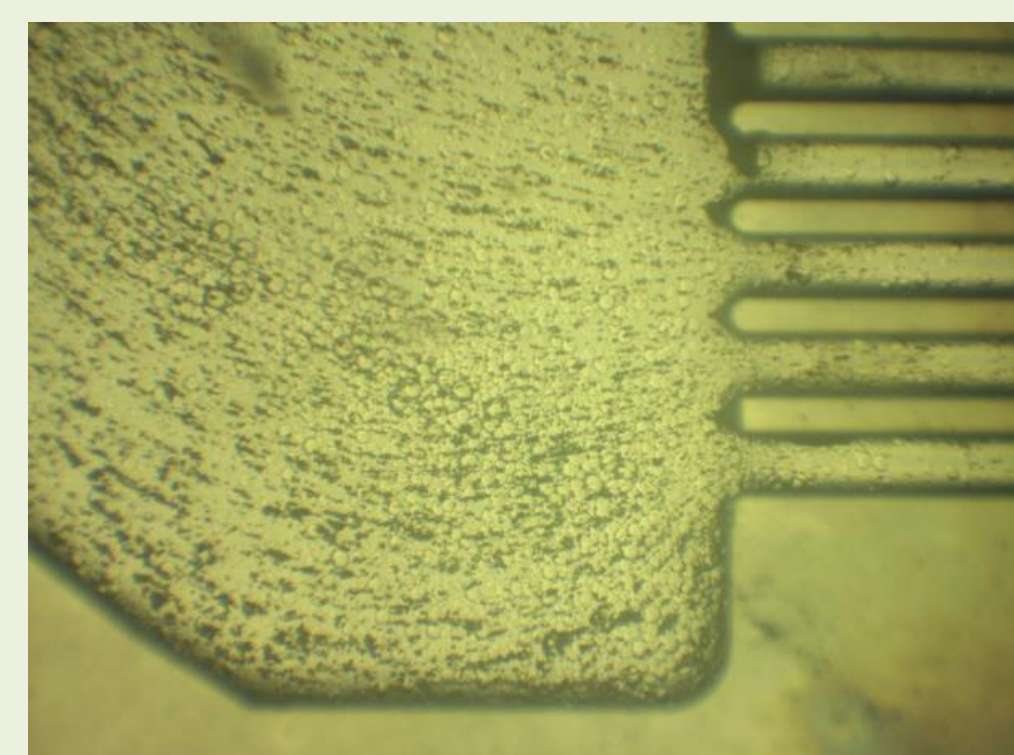
Electric Double Layer Force (F_{edl}):
Repulsion force due to the surface charges on the particles and wall.

Hydrodynamic Forces incl. Gravity (F_L , F_G):
Responsible for bringing particle close to the wall or lifting particles away from the wall.

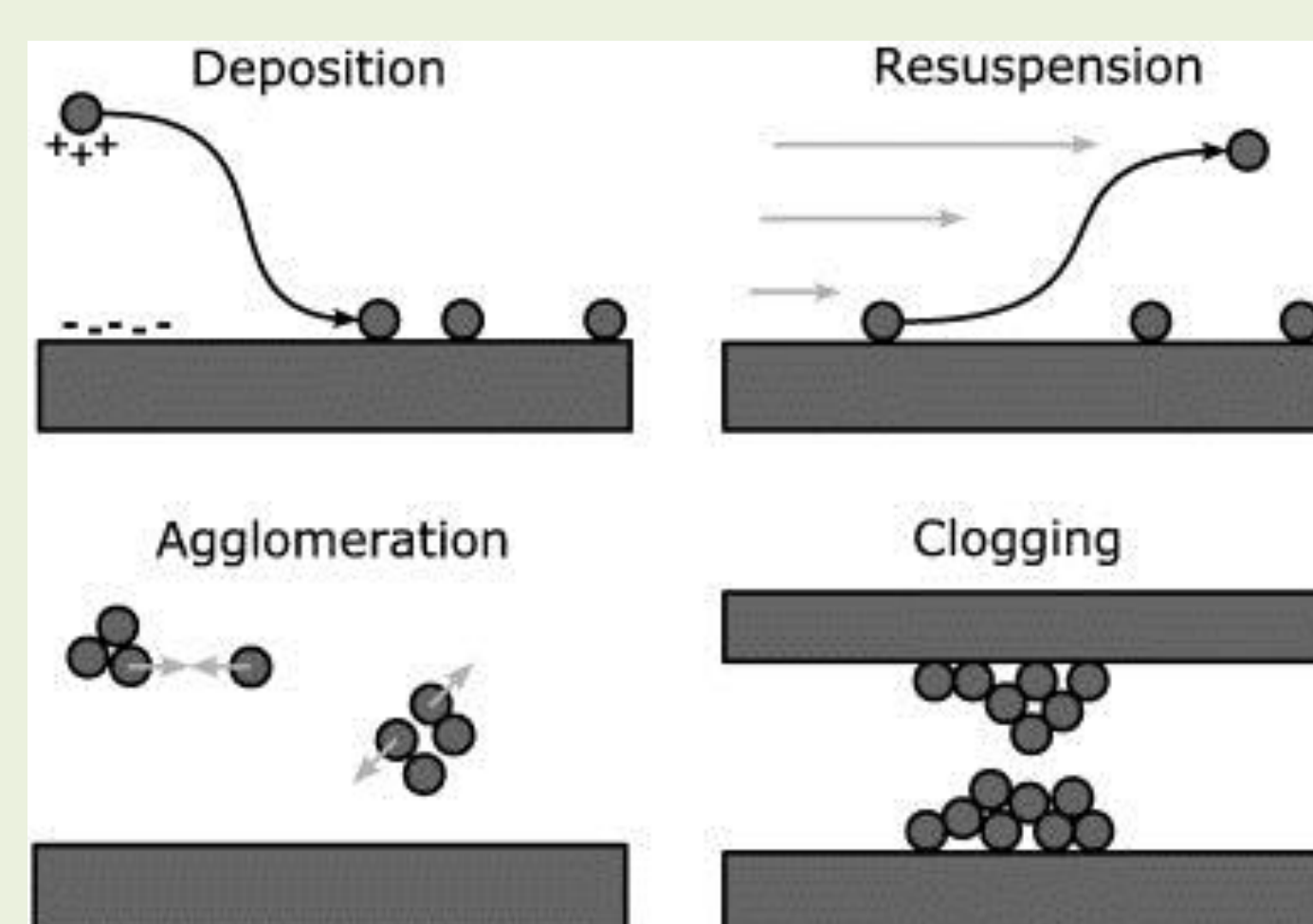


Forces involved in the fouling phenomena (Perry 2008)

Fouling/Clogging phenomena occurs when net attractive forces overcome net repulsive forces.



Clogging/fouling in the manifold region (Perry 2007)



Clogging Mechanisms (Henry 2012)

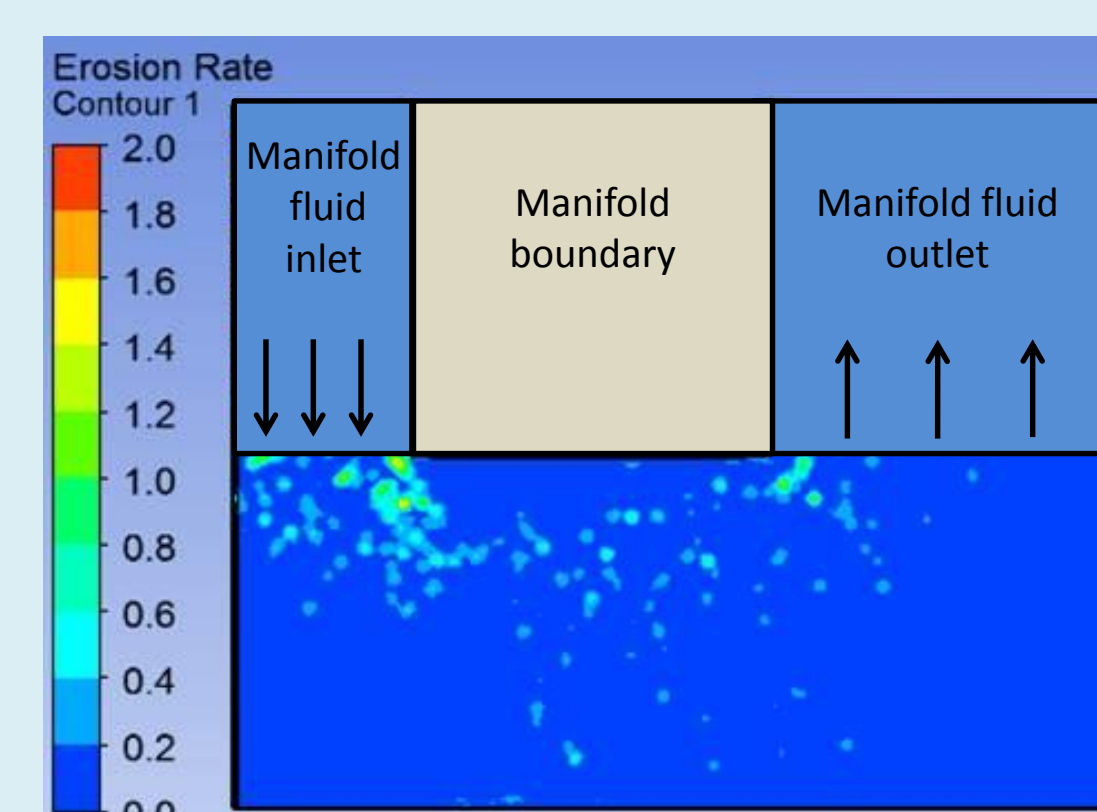
Particle Erosion Modeling of Microchannels

Particle erosion models of single-crystal silicon were used for preliminary modeling purposes. An inlet velocity of 4 m/s (single-phase fluid) was assumed to determine to effect of particle size and concentration on the erosion rate.

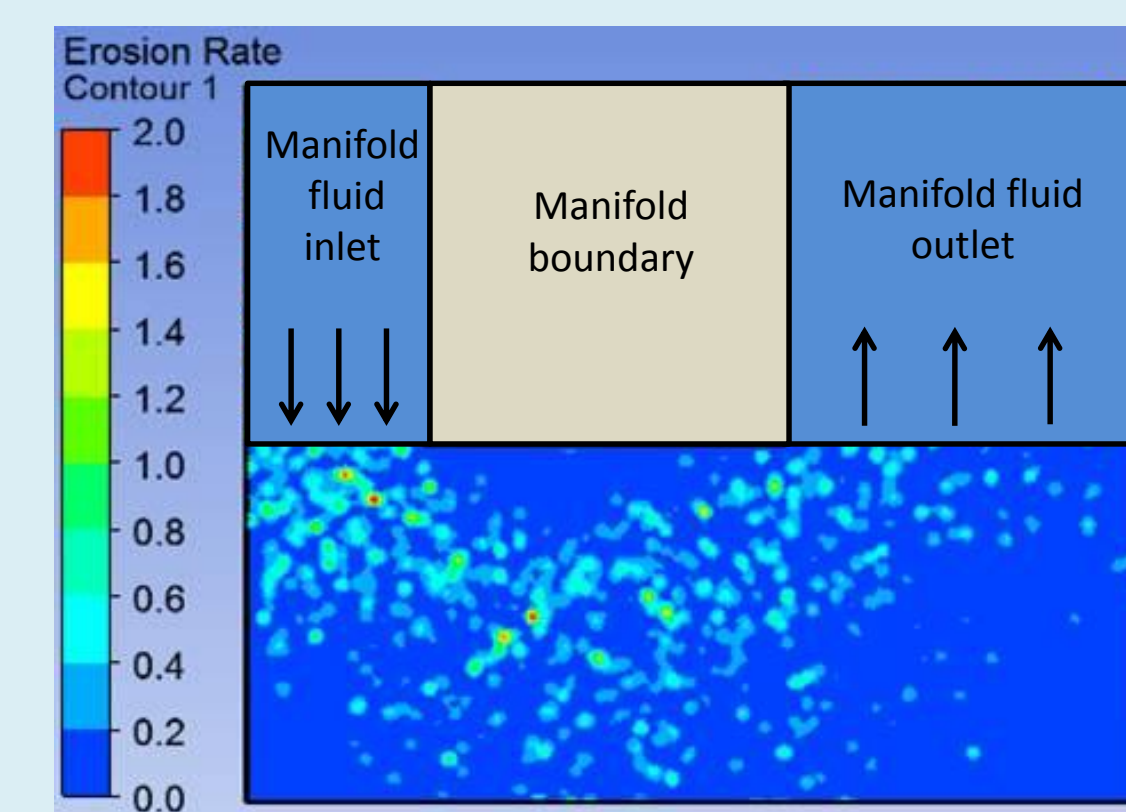
$$\Delta W = A(V \sin(\theta) - V_0)^n (D - D_0)^m$$

V_0 and D_0 assumed to be equal to 0.
Routbort and Scattergood

Operational Condition
100 nm particles 0.01% conc.



Accelerated Condition
1 μm particles 1% conc.



Units in $\mu\text{m}/\text{yr}$.

Erosion Modeling Challenges

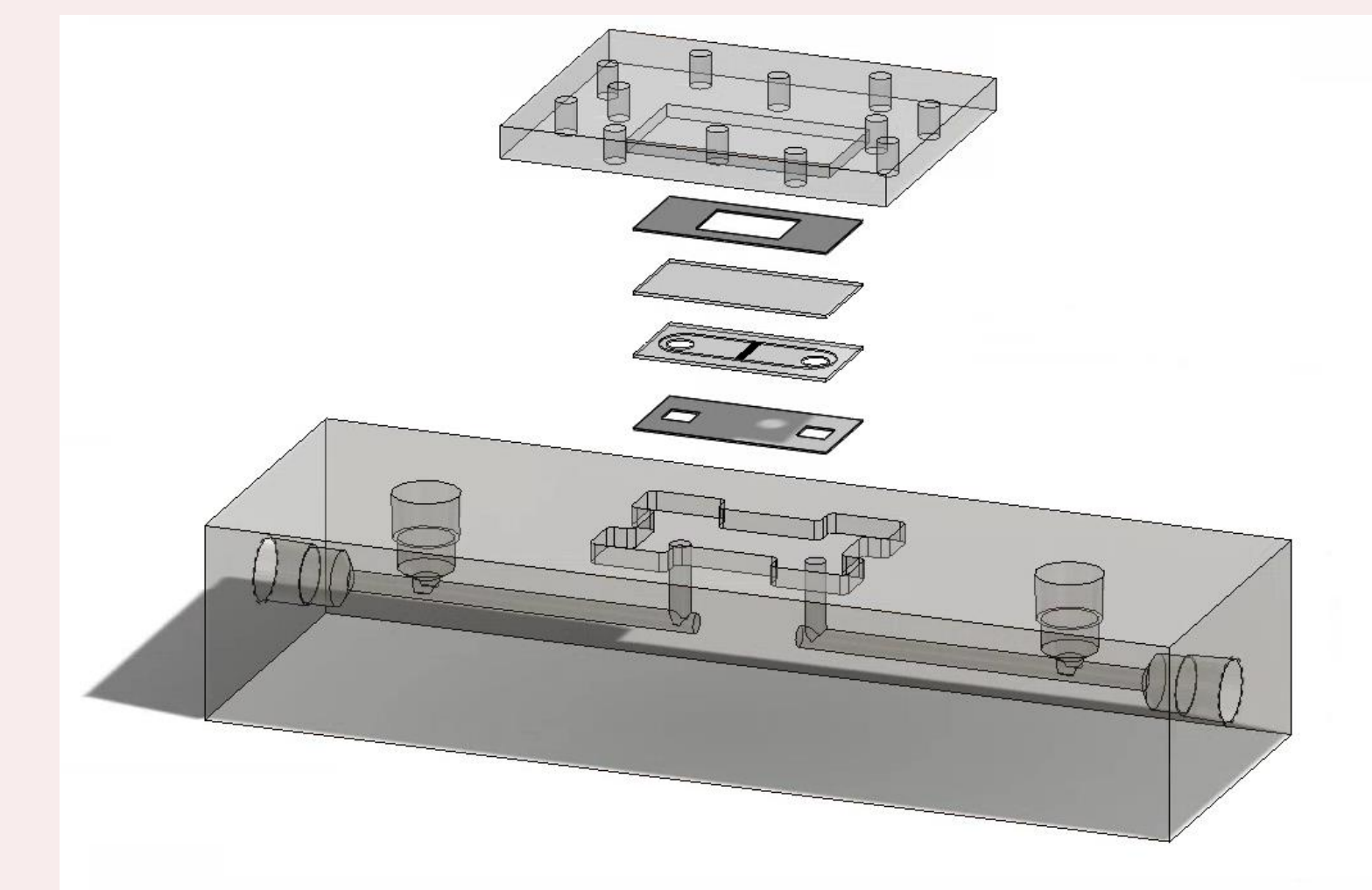
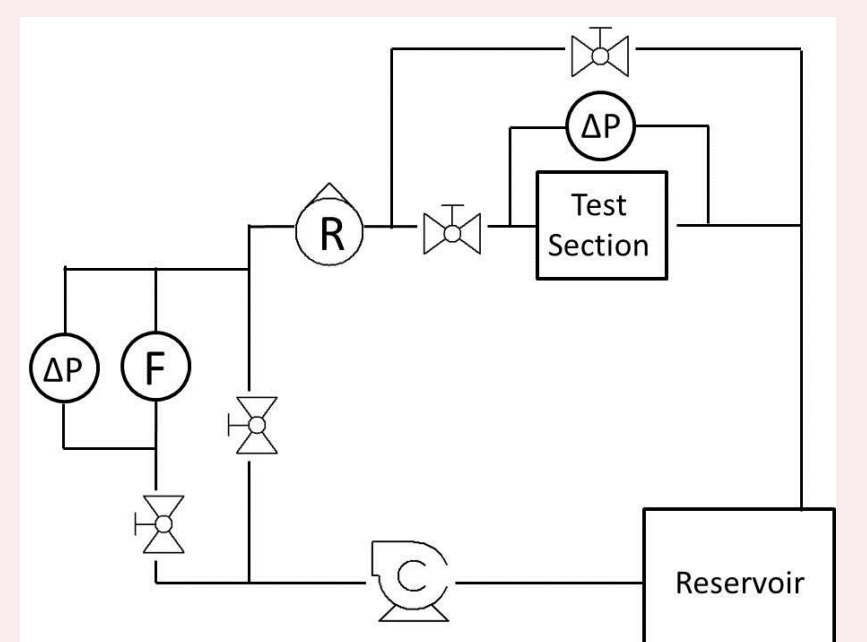
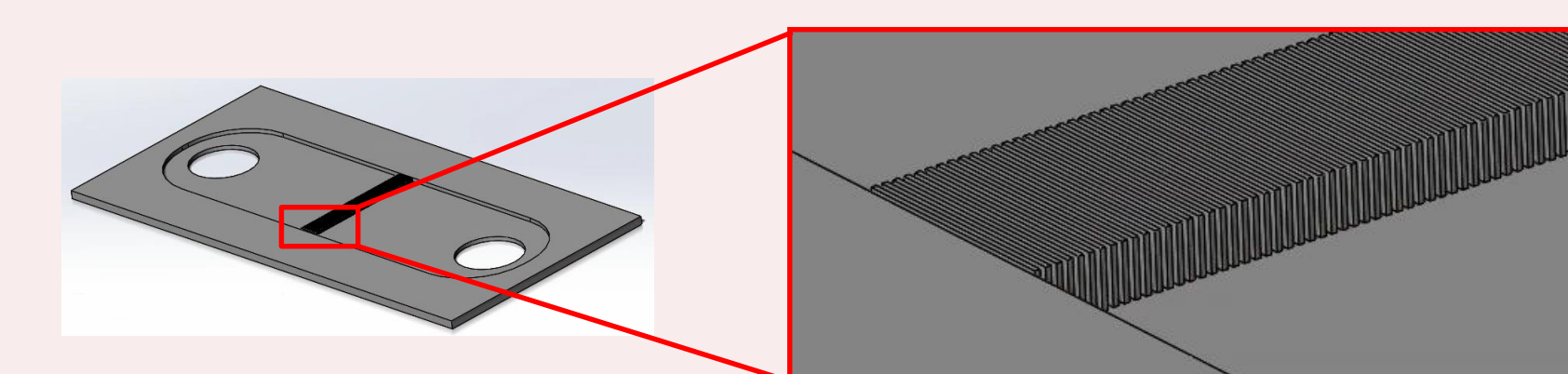
Particle erosion models developed using “sandblasting” tests.

- Significantly higher velocities and particle sizes than those present in microchannel cooling loops. Slurry erosion tests seldom include particles in the single-micron/submicron regime.
- Effect of particle-induced “squeeze-film” is neglected as sandblasting tests are performed in air.
- Difficult to capture particle-induced viscous dampening as particle approaches wall¹⁶. Requires two-way particle-fluid coupling. Very computationally expensive, difficult to achieve convergence.

Can erosion models calibrated for larger particles and velocities be used to predict erosion in microchannel coolers?

Literature suggests the existence of threshold particle and velocities under which no erosion will occur. Will this hold true over 10^2 , 10^3 ... 10^6 hours?

Experimental Clogging



- Investigate major factors contributing to clogging of microchannel coolers including particle size, concentration, pH, velocity, particulate material.
- Identify how various manifold designs impact clogging

Conclusions

- Particle erosion likely to be a concern for Si microchannels after 10^5 hours.
- Slurry erosion test apparatus has been constructed to determine threshold particle size and velocities for microchannel cooler materials.
- Clogging test setup designed to investigate major factors contributing to clogging and fouling. Identify how different manifold structures affect likelihood for clogging.

How to factor reliability in microchannel designs